Conjecture on the Appearance of the Galileo Probe's Entry and Descent into the Jovian Atmosphere

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ABSTRACT

The American Museum of Natural History (AMNH) has developed a planetarium show called *Dark Universe* that includes a depiction of NASA's Galileo Probe as it entered the Jovian atmosphere. A request was made to NASA Ames, through Mr. Charles Sobeck, to provide information regarding the possible appearance of the probe's entry. Approval has been granted by the AMNH and the IPPW International Organizing Committee to show a clip from *Dark Universe* that depicts the Galileo Probe's entry during the opening session of IPPW-11. This paper documents the information provided to the AMNH to help in making the depiction as realistic as possible. One of the descriptions is a perspective of the side view of the probe near peak heating, including the bow shock wave and the wake to a distance of ten or so body diameters behind the probe. A second description is very conjectural, and addresses the possibility of a trail of heat shield particles the probe might have left in the atmosphere during its entry. The third description shows the texture and color of the heat shield during cool down. Finally, a description of the probe's parachute is provided that was based on detailed engineering drawings of the visible parts, photographs from the build-up of the flight article, and video from the project's high altitude balloon launch test. Recently, a video called Making of *Dark Universe* has become available that depicts a few clips of the entry that can be viewed at https://www.youtube.com/watch?v=vs5tQ1H3CDQ#t=253

1. INTRODUCTION

The Galileo entry was the most severe ever encountered by an object made by human hands. The probe entered Jupiter's atmosphere at a relative velocity of 47.4 km/s on 7 December 1995 at an entry angle of -8.4 degrees from the local horizontal Reference [1]. Figure 1, from [1], depicts a cross sectional view of the Galileo Probe's deceleration module which had a carbon-phenolic fore-body heat shield and a phenolic-nylon aft-body heat shield. The probe decelerated very rapidly, encountering deceleration loads of about 250 times Earth's gravity and a heating pulse lasting about 10 seconds at half-height (Appendix A). The composition of Jupiter's atmosphere is about 90 percent hydrogen and 10 percent helium with small amounts of ammonia and methane along with other trace species including water vapor.

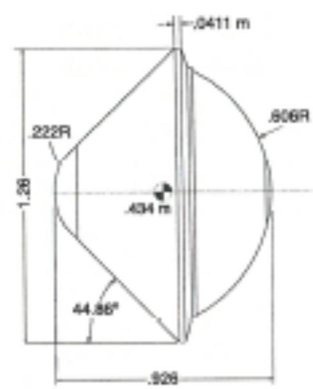
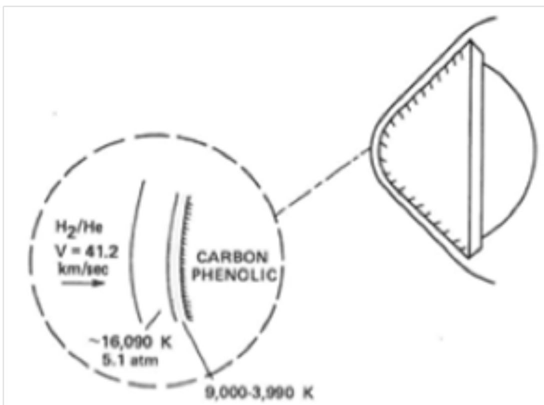


Fig. 1. Cross section of the Galileo Entry Probe from [1].

Figure 2 also displays a cross sectional view of the Galileo Entry Probe, adopted from [2]. As can be seen, it had a sphere-cone shaped fore-body heat shield and a cone angle of ~ 45^0 and a base diameter of 1.26 m.

Figure 2, adopted from [2], depicts the conditions along the stagnation stream line of the probe predicted by James Moss of NASA Langley using a computer code called HYVIS. The top part of the figure shows the bow shock wave that forms in front of the vehicle. Flow here is from left to right. The HYVIS solution suggests that about 15 percent of the shock layer is filled with carbonaceous ablation products



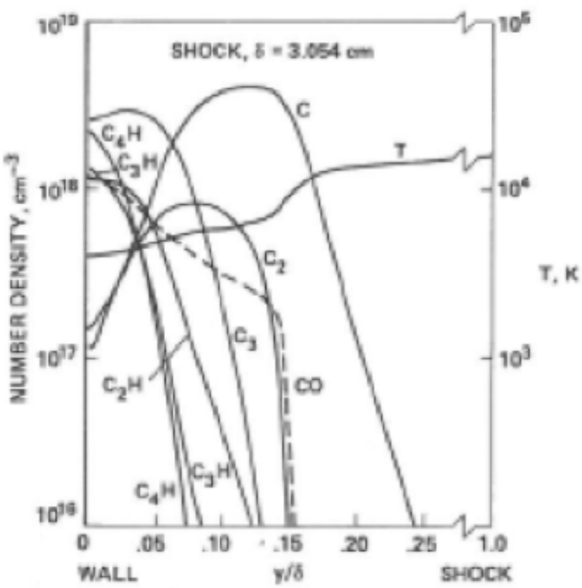


Fig 2. Conditions along the stagnation stream line for the Galileo Probe based on HYVIS predictions by James Moss at an entry speed of 41.2 km/s.

from the carbon phenolic heat shield with temperatures ranging from 3,990 K at the wall (surface of the probe) to about 9,000 K at the edge of the thick boundary layer. The concentration of the carbonaceous species in the stagnation region of shock layer is shown in the lower graph in Fig 2. Also in the graph, one can see the distribution of temperatures along the stagnation streamline. The remaining 85 percent of the shock layer in the stagnation region is filled with very hot (12,000 to 16,000 K) dissociated hydrogen and neutral helium.

The Galileo Probe was implemented with sensors that measured the recession of the carbon phenolic heat shield. Figure 3, based on data presented in [1], shows cross sectional views of the heat shield before and after entry heating was experienced. The black cross section to the left shows that the stagnation region of the un-ablated heat shield was 14.6 cm thick while it was 5.4 cm thick on the conical flank (frustum). The orange band shown to the right depicts the layer of carbon phenolic that was ablated away in only 10 seconds (Appendix A). Based on pre-flight conditions it was anticipated that severe ablation (Appendix B) would occur in the stagnation region, consequently the thickened shape there, but that the recession on the frustum would be considerably less.

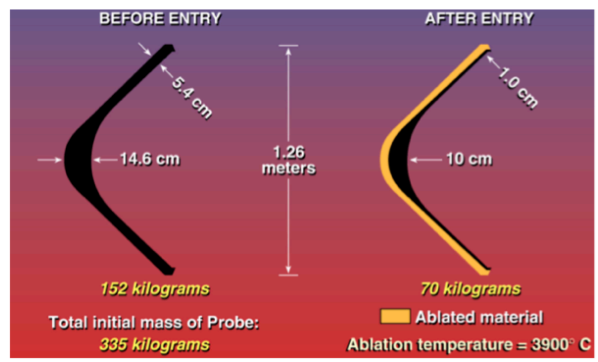


Fig 3. Cross sectional views of Galileo's heat shield before and after entry heating.

The design of the Galileo probe was very challenging because the real gas fluid dynamics codes and computers for predicting the flow environment were primitive compared to those available today. Also, the materials properties of the carbon phenolic heat shield material were not well known. It is possible that the blockage of the intense radiation from the hot hydrogen in the shock layer by the boundary layer was under-predicted owing to a lack of understanding of the properties of the carbonaceous species. Further, it is believed that the excess recession on the frustum may have been caused by turbulence induced surface roughness and spallation (Appendix B) of the heat shield. Spallation is a mechanical erosion of the heat shield that does not contribute to thermal protection as does the ablative process where pyrolysis of the material provides energy management by a controlled loss of material. In retrospect, the large amount of recession on the frustum indicates that the Galileo entry was a "near miss" failure owing to how close the heat shield came to burn-through on its conical flank.

2. COLOR OF THE BOW SHOCK WAVE

The data from Fig. 2 shows that the outer 85 percent of the shock layer is mainly hot hydrogen with some atomic carbon. In the side view line of sight, temperatures would be in the range of 12,000 to 16,000 K throughout the bow wave. It is believed that the color of the bow shock wave from the side would be bluish-white because Planck's black-body spectrum at those temperatures peaks at about 3,000 Angstroms. The source of the radiation is from a blend of hydrogen continuum and from carbon and hydrogen atomic lines.

Figure 4 is a side view of a small carbon phenolic model of the Galileo Probe flying in a chamber filled with krypton at 100 Torr [3]. The luminosity of the side view of the bow wave gives an idea of what the Galileo probe's appearance was during its high - speed entry. Based on discussion above, the arrow-shaped bow wave denoted by (1) would appear to be bluish-white in flight.

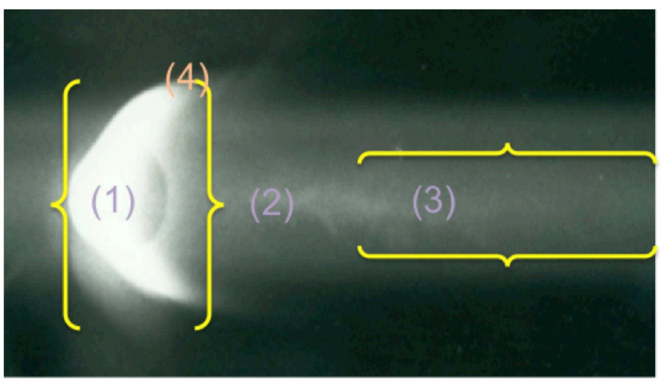


Fig 4: Image of a small model of the Galileo Probe flying into 100 Torr of krypton at 4 km/s. The brackets and numerals specify regions discussed in the text. An unmarked version of the figure is contained in Appendix C.

3. COLOR OF THE BASE RE-CIRCULATING REGION

Figure 5, adopted from [4] with the description on pages 203 to 206 from [4], explains the general shape and conditions of after-body and wake flows during hypersonic flight.

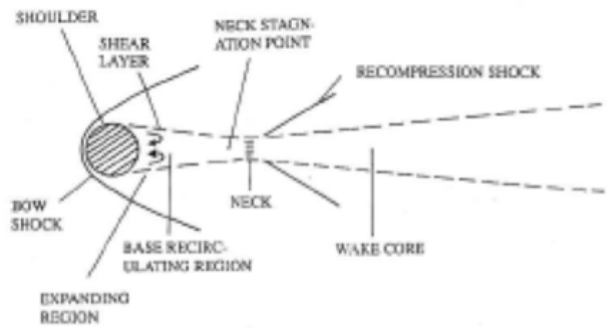


Fig 5. Structure of after-body flows during hypervelocity flight [4].

The base re-circulating subsonic flow region depicted as (2) in Fig. 4 is quite hot, and should also be colored bluish-white. The pressure is much lower here, so its integrated intensity is roughly a factor of 1/8 that of the bow shock. The relative factors of integrated intensity at various distances behind the model can be deduced from the output of the photo detector [3] shown in Fig. 6. The detector viewed the model through a narrow slit as it flew in a ballistic range. This model was made of carbon phenolic and flew into 100 Torr of Krypton at 4 km/s. Region (2) will feature undulating eddies in the flow and while faint, they can be seen in the unmarked version of Fig. 4, contained in Appendix C.

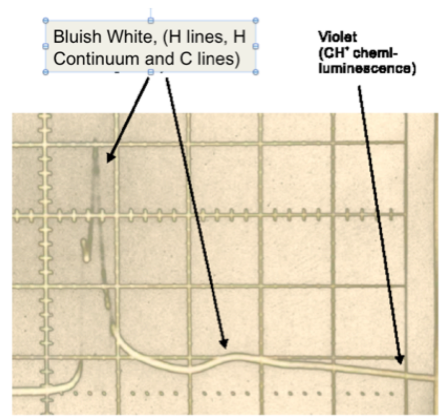


Fig. 6. Output from a photo detector viewing the Galileo Probe model and its after-body/wake flow.

4. COLOR OF THE WAKE DOWNSTREAM OF THE AFT STAGNATION POINT

In flow Region (3) (Fig 4), the color should blend to become violet because the major contributor to the wake flow is from CH^+ chemiluminescence, which arises from these reactions:

$C^+ + H_2 \rightarrow CH^+(B) + H$
$CH^+(B) \rightarrow CH^+(A)$ + photon (3400-3500 Angstroms)
$CH^+(A) \rightarrow CH^+(X)$ + photon (3730-4800 Angstroms)

The B state is singlet-delta, the A state is singlet Pi, and the X state is singlet sigma.

Because this reaction requires the presence of $C^{+,}$ the length of the chemiluminescence trail is that of C^+. According to the data presented on page 205 in [4], ballistic range testing indicates that electrons persist up to about 20 body diameters in the wake flow. Thus one could say that chemiluminescence could persist to that distance. Since the integrated intensity falls off with distance behind the body, it could be that the wake radiation dies out after about 10 body diameters. Because of the differences in the planetary atmospheres and involved chemistry, this situation is very different from hypersonic flight through the Earth's atmosphere, or in the Martian atmosphere. An observation of a shuttle entry shows a visible trail about 70 km long [5]. In the Martian atmosphere, CO chemiluminescence will produce a similar phenomenon. However for the Jovian entry, the CH^+ chemiluminescence will persist only for 10 to 20 body diameters.

5. CONJECTURE REGARDING A TRAIL OF CARBON PHENOLIC PARTICLES BEHIND THE GALILEO PROBE.

If spallation of the carbon phenolic occurred in the frustum of the fore-body heat shield, a sheath of small carbon particles would be shed from the probe's shoulder region [See Region (4) in Fig. 4]. An idea of what such a sheath might look like can be gained by looking at Fig. 7 that shows a side view of a water cooled wedge in an arcjet flow which had a seamed carbon fabric held on its face to test its aerothermal performance [6]. Carbon particles shed from the fabric and seam can be seen in the flow as it exits from the aft, left end of the wedge. The material shed from the Galileo Probe's flank would probably have looked similar to that seen in the arcjet flow. Since the carbon particles are massive, they would tend to not be inertially coupled to the gas flow.

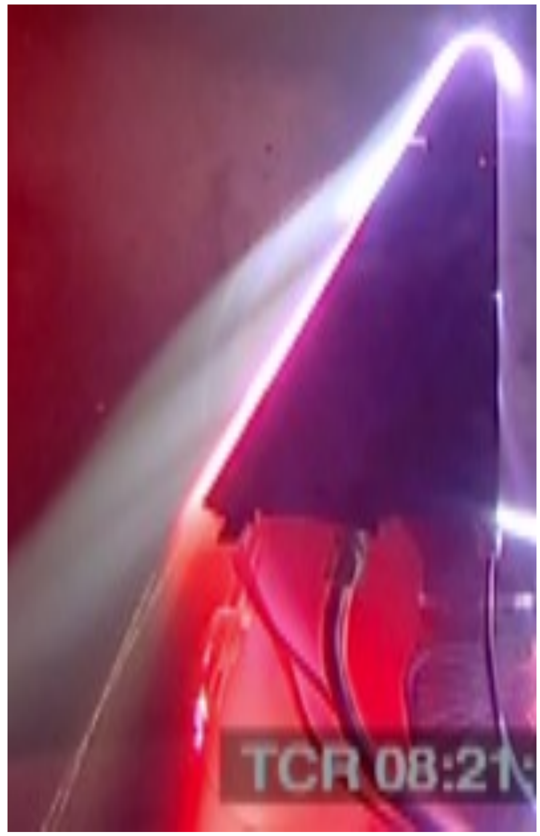


Fig. 7. Still image of glowing carbon particles being shed from the aft flank of an arcjet test flow [6]. Flow direction in this figure is from top to bottom.

If particulate carbon was spalled and entrained in the flow, the sheath would glow red for a short distance behind the shoulder since it would be shed at around 3900 K. The particles would then cool, having the black appearance of the virgin heat shield material. If this happened, there might be a cylindrical shaped trail of small black particles that might persist for a considerable distance along the Probe's flight path.

6. TEXTURE OF THE HEAT SHIELD MATERIAL AFTER ENTRY HEATING

The texture or the TPS post-heating was estimated to appear similar to that from a small model made of carbon phenolic that was recovered from a ballistic range test as shown in Fig. 8. The template above the model depicts the pre-flown shape of the sphere-cone model and the white ruler gives the model's scale. The roughened surface of the model is about that of 60 grit sandpaper. The peak surface temperature would be ~ 3900 K and would slowly cool once the entry heating profile is completed.

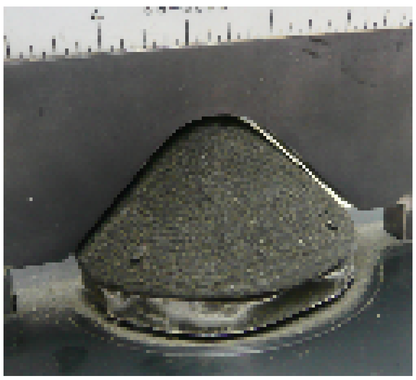


Figure 8. Recovered model made of carbon phenolic recovered from a ballistic range test.

7. PARACHUTE

The parachute system for the Probe has been documented in several technical papers [7,8,9,10]. While these technical descriptions provide some insight as to the general configuration of the parachute system, they do not provide sufficient detail regarding appearance, especially during flight. Fortunately, NASA had published a YouTube™ video [11] from the parachute system aerial drop test or Integrated System Test (IST). This test was conducted via release from a high altitude balloon gondola and subjected the system to flight-representative aerodynamic conditions. As the system was deployed from a flight-representative capsule, the up-look film footage provided a very reasonable facsimile of the actual flight appearance (Fig. 9). AMNH videographers/animators digitized the available footage and used it extensively to generate the very realistic deployment and inflation of the parachute system.

Figure 9. Galileo IST "Up-Look" Showing Main Canopy through 3-Leg Bridles Attached to Swivel.

For extreme details regarding the appearance of various components that were not clear in the 30 year old digitized film footage, actual technical drawings and/or photographs from the flight unit manufacture/assembly were used. In at least one case, the main parachute swivel, a part from the flight lot was located and used for appearance. For this particular part, the packaging procedure required that the swivel be enclosed in a soft cover in order to prevent it from damaging the close contact parachute canopy fabric. No images or descriptions of this soft cover existed, so a new one was generated from the technical drawings and installed on the existing swivel (Fig. 10). The resulting animation images of the parachute system in *Dark Universe* are, therefore, as accurate as physically possible.

Figure 10. Galileo Probe Main Parachute Swivel with "Boot".

8. SUMMARY

Providing technically realistic descriptions to the AMNH for the appearance of the Galileo Probe during entry and descent into the Jovian atmosphere was an interesting challenge. Answers had to be produced in a short time to meet production schedules for *Dark Universe*. The work considered a combination of data sets from 30-year probe research results, engineering design data and from ground-based experimental results. These results were then used to make engineering judgments to conjecture on what the Galileo Probe's entry actually looked like.

A much more accurate description could be provided if a state-of-the-art 3-D flow-field computational simulation, including the wake flow, of the Probe's flight entry was available. It would include validated models for the complex physical phenomena for the coupled chemistry, radiation, turbulence, massive heat shield ablation and spallation. Currently, we do not have this capability, but it is within technical reach of the planetary probe community. Such work would be extremely valuable for the design of new probes to return to Jupiter or to the other gas giants such as Saturn.

9. REFERENCES

[1] Milos, F. S., Chen, Y-K, Squire, Thomas H. and R. Brewer, *Analysis of the Galileo Heat Shield and Temperature Data*, AIAA Paper 97-2480, 1997. Also, *Planetary Mission Entry Vehicles,* NASA Ames Reasearch Center, Vol 1.0

[2] Arnold, J. O., Cooper, D. M., Park, C. and Prakash, S.G., *Line-by-Line Transport Calculations for Jupiter Entry Probes, Progress in Astronautics and Aeronautic*s, AIAA New York, 1980, pp 52-82. See Also *Planetary Mission Entry Vehicles,* NASA Ames Research Center, Version 1.0, 2002

[3] Park, Chul, Private Archives.

[4] Park, Chul. *Nonequilibrium Hypersonic Aerothermodynamics* , John Wiley and Sons, Inc, 1990.

[5] http://www.popsci.com/technology/article/2011-07/one-last-pic-atlantiss-glowing-re-entry-captured-iss

[6] J. O. Arnold, M. de Jong, D.K. Prabhu, T. Boghozian, S. Gorbunov, C. Kruger and A.M.Cassell Arcjet Testing of Woven Carbon Fabric Seams for Adapative Deployable Entry Placement Technology, IPPW-11 Pasadena CA, June 16-20, 2014.

[7] McMenamin, H.J., *Galileo Parachute System Performance*, AIAA Paper 97-1510, 1997.

[8] McMenamin, H.J., Pochettino, L.R., *Galileo Parachute Modification Program*, AIAA Paper 84-0824CP, 1984.

[9] Corridan, R.E., Givens, J.G., Kepley, B.M., *Transonic Wind Tunnel Investigation of the Galileo Probe Parachute Configuration*, AIAA Paper 84-0823, 1984.

[10] Rodier, R.W., Thuss, R.C., Terhune, J.E., *Parachute design for the Galileo Jupiter Entry Probe*, AIAA Paper 81-1951, 1981.

[11] http://www.youtube.com/watch?v=9olyvfRtJEc&list=PL4C59D9730551324F&index=64

10. ACKNOWLEDEGMENT

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Appendix A: Comparison of Predicted and Measured Recession in the Stagnation Region of the Galileo Probe's Entry Into the Jovian Atmosphere

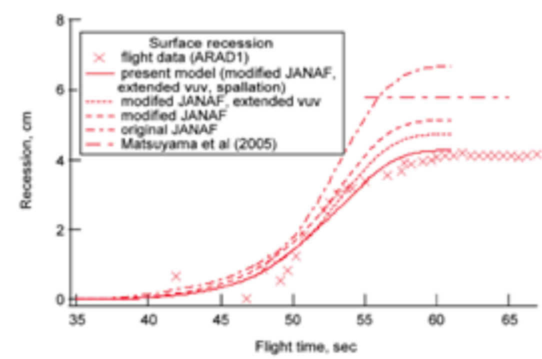

Fig. A1. Measured (flight data) and calculated history of surface recession at the stagnation point, taken from C. Park, "Stagnation-region heating environment of the Galileo Probe," Journal of Thermophysics and Heat Transfer, Vol. 23, No. 3, July-September 2009, pp. 417-424.

Appendix B: Ablation and Spallation

Ablation: Ablative thermal protection systems have been used since the dawn of the space age and various materials have been flown, e.g. the AVCOAT material flew on the Apollo return modules and the Mars Science Laboratory (MSL) entry vehicle flew a lightweight phenolic impregnated carbon ablator (PICA). As discussed above, Galileo flew a very robust ablator known as carbon phenolic on its forebody. Virgin carbon phenolic is a composite of carbonized rayon fabric layers that has been impregnated with a phenolic resin. Figure B1 depicts the process of ablation.

Note the thermal protection system (TPS) layup where initially a thickness of virgin material is bonded to a carrier structure (denoted backup material in Fig B1). By use of a thermal response model for the TPS, the thickness of the virgin material is "sized" to maintain the bondline between the TPS and the backup material until such time that the heat shield has served its function. The Galileo Probe fore-body TPS was sized to maintain the TPS bond line at a temperature of 644 K [1], (page 5).

During entry, a bow shock wave forms over the vehicle and the ablator heats. For the Galileo Probe, the bow shock layer imposed an intense coupling of radiative and convective heating on the carbon phenolic heat shield. This heating soaks into the TPS and three zones form: the virgin material, the pyrolysis layer and finally the char layer. In the pyrolysis zone, the heat causes the solid carbon phenolic to decompose into a complex mixture of carbonaceous species. The act of decomposition absorbs energy, reducing the amount of energy available to conduct through the remaining material. The char zone is porous and completely devoid of the phenolic. During ablation, the pyrolysis gases, created in depth at a cooler temperature, flow through the char, cooling the char, and into the boundary layer, thickening it, which is relatively cool compared to the shock layer as shown in Fig. 2. The thick boundary layer protects the vehicle's outer mold line, and in the case of Galileo provides blockage of the intense shock layer radiation by the boundary layer species.

Concisely, an ablator works by the process of energy management through the consumption of the TPS by pyrolysis and surface reactions with the boundary layer gases. As the consumption proceeds, the TPS recesses. The ablator is self-regulating because increased heating causes increased material consumption and the recession to proceed faster.

The challenge to the heat shield designer is to provide sufficient margin in the TPS thickness so the ablator maintains the bond line at the design temperature. This design requires a thermal response model that is based on testing in ground facilities that can simulate the aerothermodynamic heating to the vehicle during its entry. Usually the ground facility is an arcjet where the electrically heated test gas flows over a sample of the TPS material. The thermal response model must be capable of predicting the in depth temperature distribution in the TPS and its recession during the entry heating.

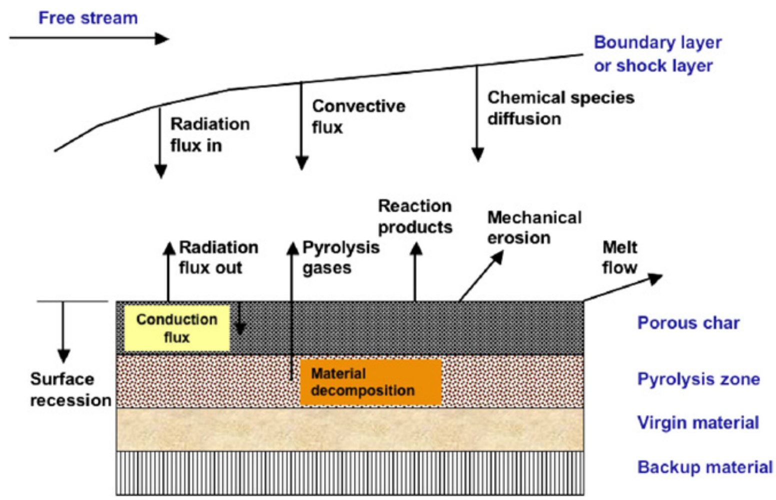

Fig B1. Depiction of the ablation process.

Spallation: In Fig. B1, there is a notation "mechanical erosion". One process of mechanical erosion is spallation, where internal pressure from the pyrolysis gases causes flakes of the ablator to "pop off" into the flow. This loss of material causes recession of the ablator but does not contribute to thermal protection, since there is little to no pyrolysis of the flaked particles. Testing of spallation was done for the Galileo mission by laser illumination. For the flight case, is difficult to know how much of the recession on the frustrum was caused by spallation and how much was caused by enhanced heating by surface roughening from the turbulent heating.

Appendix C: Unmarked copy of Ballistic Range Model in Flight

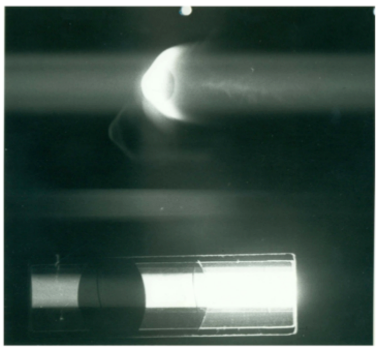

Fig C1. Image of a Galileo ballistic range model made of carbon phenolic flying into 100 Torr of Krypton at 4 km/s.